Application of Superconductors for Automobiles

Hitoshi OYAMA*, Tsuyoshi SHINZATO, Kazuhiko HAYASHI, Kenji KITAJIMA, Tsuyoshi ARIYOSHI and Takanori SAWAI

In recent years, global warming has become a serious environmental issue. Development efforts are currently underway toward achieving practical application of high-temperature superconducting wires. A high-temperature superconductor has zero electrical resistance at the temperature of liquid nitrogen, so it can reduce the power losses in electrical equipment. The authors have developed a prototype electric vehicle equipped with a motor system that uses bismuth superconducting wire to verify the potential and problems of superconductors. It was verified that the prototype superconducting motor has a torque of 70 Nm, an output of 18 kW and a maximum speed of 70 km/h. The maximum torque can be achieved at low rotations, and therefore a smooth start and acceleration is possible. After six months of test driving, there has been no problem.

1. Introduction

As environmental problems have become serious global concerns in recent years, researches are in progress on high-temperature superconducting wire. High-temperature superconducting wire, whose electrical resistance is zero at liquid nitrogen temperatures, now shows dramatic improved in performance and is experimentally applied to electric power cables, ship engines and other applications [(1)-(3)]. Yet there are little published researches on the use of superconducting technology to power land transport vehicles in the field of automobiles. The authors have developed an engine using bismuth superconducting wire and mounted it in an electric car, in order to investigate the potentials and challenges of applying superconducting wire to automobiles.

2. Global Warming Issue

2-1 Serious Global Warming

In recent years, the frequency of extreme climatic events is increasing on a global scale, and global warming has become one of the top diplomatic agendas. Although some observers claim that the recent worldwide temperature rise is nothing more than a part of the Earth's 100,000-year climate cycle of glacial and interglacial periods, it is clear that during the two centuries since the start of the Industrial Revolution, the rate of temperature increase has been ten times higher than that during previous interglacial periods. It seems that the debate that has spanned some twenty years is coming to a close, with a conclusion that global warming is caused by anthropogenic emissions of greenhouse gases. The Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change issued in 2007 [(4)] projects that by the end of the 21st century the global average temperature will be 6.4°C higher at most than it was at the end of the 20th century. The report also warns that the global environment will deteriorate at an accelerated pace if human society continues to prioritize fossil-fuel-based economy over environment.

2-2 The Kyoto Protocol

The Kyoto Protocol adopted in December 1997 at the Third Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 3) sets the levels of future greenhouse gas emissions for participating countries based on the 1990 levels. The average carbon dioxide (CO_2) reduction target for developed countries during the five year period from 2008 is 5% [(5)], including a 6% reduction target for Japan. In order to curb global warming, the Kyoto Protocol obligates each participating country to set emissions reduction policies, and creates the mechanisms of international cooperation such as emissions trading. It is an initiative for resolving environmental problems on a global scale.

2-3 Control of Total CO_2 Emissions

Japan's major industries have the world's highest levels of energy efficiency, as they have been accumulating proprietary energy-saving technologies since experiencing the two oil crises of the 1970s. Where energy consumption per real GDP calculated from the 2003 statistics in Japan is 1.0, the United Kingdom is 1.43, the United States is 2.06, and Germany is 2.41. This clearly indicates the highly efficient energy use by the Japanese industries. Yet it is not easy to effectively control total CO_2 emissions (i.e., reduce energy consumption) while maintaining a certain level of economic growth (change in GDP). While Japan is required by the Kyoto Protocol to reduce its CO_2 emissions by 6%, the actual plan is to achieve the target through a combination of emissions reduction (0.6%), forest absorption (3.8%) and emissions quota trading (1.6%). However, along with the upswing of the Japanese economy, the year 2006 saw not a reduction of CO_2 emissions, but rather a 6.4% increase. In order to meet the target by 2012, additional measures will be implemented to reduce 2.7% of the country's total emissions. These measures include enhancement of CO_2 emissions reduction efforts by the industrial sector under the voluntary action plan and promotion of popular-participation-type movement for saving energy in homes, automobiles, offices, etc. In the transport sector, which generates 23% of total CO_2 emissions in Japan, CO_2 emissions are forecast to increase by 10% to 12% in 2010, and therefore the sector is likely to come under pressure to significantly improve fuel efficiency.

Considering Japan's position as a nation committed to environmental protection, there is no doubt that the promised target to be met by 2012 should be achieved. Yet in the post-Kyoto Protocol period from 2013 onward, there are likely to be considerable continuing obligations for further CO_2 curtailment. In order to bring about a sustainable low-carbon society where both environmental protection and economic growth can be achieved, it is absolutely necessary to develop revolutionary technologies for the future.

3. Trends in Environmentally-Friendly Vehicle Development, and Superconducting Motor

The great majority of land-transport machines (mainly automobiles) consume large quantities of petroleum, either in the form of gasoline or diesel fuel. To cope with the issues of depletion of fossil fuels and global warming caused by CO_2 emissions and realize sustainable motorization, significant improvements in energy efficiency and shift to non-petroleum alternative fuels are required. There are mainly three types of environmentally-friendly vehicles under development by automakers and research institutes: Hybrid electric vehicle (HEV), electric vehicle (EV), and fuel cell vehicle (FCV) [(6), (7)].

HEVs are under mass production since 1997, spreading much faster than EVs or FCVs. Because HEVs use a combination of a gasoline engine and an electric motor, the existing infrastructure for gasoline-driven vehicles can be utilized. EVs and FCVs, meanwhile, produce zero emissions during operation, making them the ultimate eco-cars. EVs offer strong overall improvements in energy use and environmental impact, as electricity is available with relatively low petroleum use. Instead, EVs rely on low CO_2 emitting energy sources such as nuclear power, gas power, and hydraulic power. FCVs likewise provide substantial reduction of CO_2 emissions, as hydrogen used as a fuel can be produced from various clean energy sources. FCVs are expected to spread rapidly and replace the conventional internal combustion engine vehicles in the future, once improvement is seen in terms of battery capacity, cost, and infrastructure installation.

What these three types of environmentally-friendly vehicles have in common is the use of electricity to deliver power from a motor. Realizing high efficiency, high performance motor is the key to the development of electric vehicle systems. Thanks to recent improvements in the performance of high-temperature superconducting wire and in the adiabatic cooling technology, the feasibility of more efficient electric vehicle system by applying superconducting motor is being actively investigated.

Figure 1 shows the features of a superconducting motor coil. A superconducting coil provides a high magnetic flux density, and therefore delivers much higher torque than ordinary motors. Also, a superconducting motor can be used without copper loss, and an air-core superconducting motor may be developed in the future to reduce iron loss and increase motor efficiency. The drive range of an automobile motor is wide, from low to high speeds and from low torque for constant-speed cruising to high torque for acceleration. While an ordinary motor exhibits increased copper loss and poor efficiency during high-torque output, a superconductive motor provides high efficiency over a wide range.

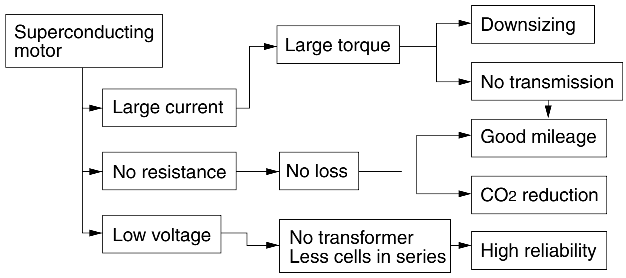

Fig. 1. Features of superconductor motor

The structure of a system for applying superconductivity to an ordinary electric car engine is shown in **Fig. 2**. With an ordinary motor, drive power is supplied in different revolution speed ranges, from several thousand to more than ten thousand RPM, and variable-speed gears are used to reduce the revolution speed and increase the torque. A superconducting motor, on the other hand, would supply much higher torque, so the system can be designed with the motor directly driving a shaft, without variable-speed gears. This should allow the reduction of transmission loss caused by the gear system.

The challenge in applying a superconducting motor to an automobile is that the superconducting coil must be kept at a low temperature, below the critical temperature of the superconducting material. A refrigerating mechanism is required, as it is necessary for the coil to be at a low temperature at the time it is utilized, and it is necessary to keep it at a low temperature using a refrigerating unit while the vehicle is in operation. Therefore, it is most advantageous to use such a system in vehicles that are utilized at a high rate of operation.

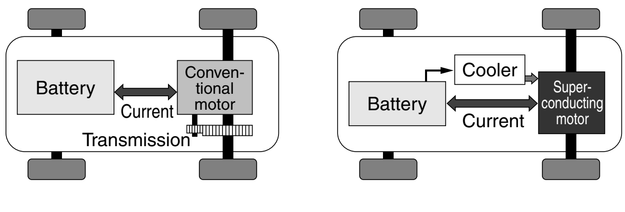

Fig. 2. System configuration

Also, in a heavy vehicle that requires a high output, the output of the cooling mechanism has less impact on the increase of motor efficiency and the decrease of transmission loss. Furthermore, because high output is required during acceleration or deceleration regeneration of a heavy vehicle, superconducting motor would also be suitable for buses and other mass-transit vehicles that experience frequent stop-and-go operations.

4. Prototype Superconductive Motor

4-1 Principle, Wire, and Specifications

The specifications of the tested motor are shown in **Table 1**. In terms of basic principle, it is a series-wound DC motor with a coil formed of the polyimide-film-wrapped type-H superconducting wire to provide a constant field. The superconductive coil is immersed in liquid nitrogen for refrigeration, and a stainless-steel cooling insulation vessel with a vacuum layer is used. The iron core consists of four claw poles. The coil is a simple pancake coil formed of 186 turns of superconducting tape. The claw pole design was adopted to enable larger coil winding radius and thus reduce the number of coils, and to simplify the design of the cooling apparatus and other elements. Because the motor has a long shaft, the coil is divided into two parts as shown in **Fig. 3**. The same armature rotor as that used in a commercial DC motor is used.

Table 1. Specifications

Wire	Wire type	Type H (polyimide film insulated)
	Dimensions	4.2 × 0.22 mm
	Critical current (Ic)	140A
	Maximum tensile strength (77K)	150MPa
	Minimum bend radius (room temperature)	70mm
Coil	Shape	Inner dia.: 186 mm Outer dia.: 210 mm Width: 40 mm
	Turns	186 turns / coil
Motor	Motor type	Series-wound DC (field superconductor)
	Coil refrigeration method	Liquid nitrogen immersion
	Maximum voltage	144V
	Maximum current	500A
	Dimensions	267 (dia.) × 370 (height) mm
	Weight	About 70 kg

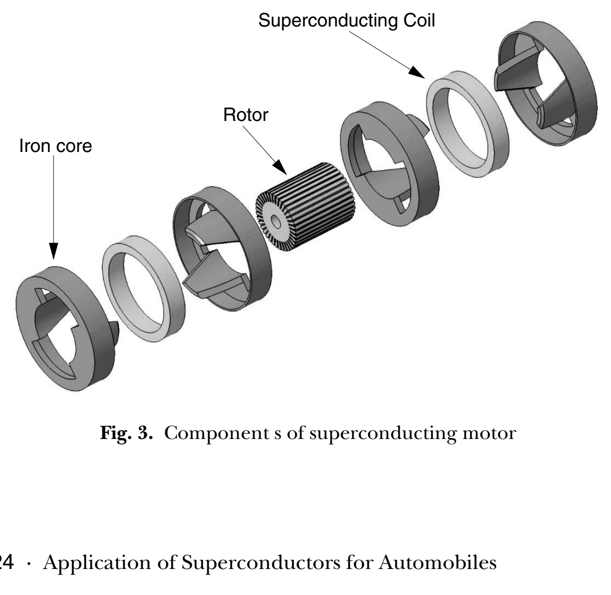

Fig. 3. Component s of superconducting motor

4-2 Design

In designing a motor using a superconductive coil, the configuration of claw poles was determined by means of CAE analysis of magnetic flux density distribution and magnetic saturation. **Figure 4** is an example of an analysis image. In **Fig. 5**, the measured torque values are plotted over the designed current/torque characteristics of the motor. The measured drive torque of the motor mounted on a vehicle was very close to the design value of 58 Nm at a maximum current.

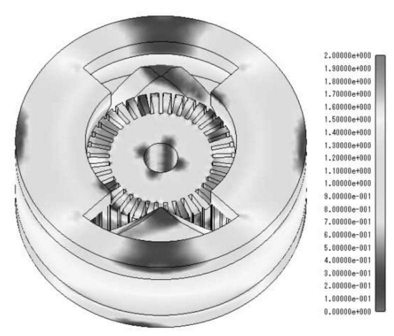

Fig. 4. Contour of flux density

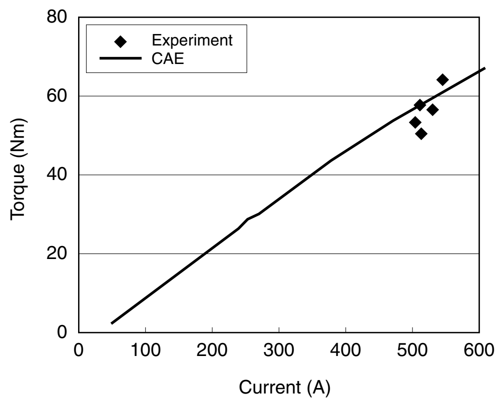

Fig. 5. Torque curve of superconducting motor

4-3 Construction and Appearance

Photo 1 is an exterior view of the superconducting motor. The superconducting coil is immersed in liquid nitrogen inside the thermal insulation vessel, and it is necessary to compensate for liquid nitrogen evaporated during motor operation. To provide a continuous supply of liquid nitrogen during operation, liquid nitrogen reservoirs are included at the top of the motor.

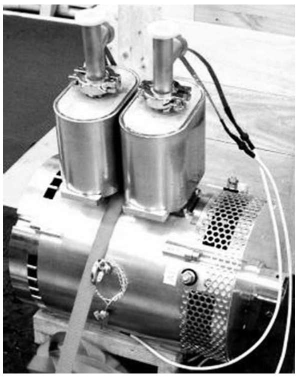

Photo 1. Superconducting motor

5. Prototype Superconductive Electric Car

A previously published study described the successful operation of a golf cart using a bulk superconductor with an output of 2 kW[8]. In the present study, the superconducting motor has been mounted on a commercial gasoline car (a Toyota Probox) so as to retrofit the vehicle as an electric car and verify its practicality in a vehicle environment that approximates normal use. The drive system of the prototype vehicle is diagrammed in **Fig. 6**. The power source for the motor is twelve 12-V lead batteries connected in series (144 V).

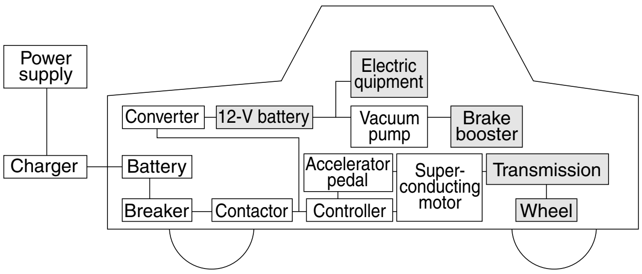

Fig. 6. Configuration of superconducting car

The pressure on the accelerator pedal is measured with a sensor, and a commercial current controller is used for supplying the corresponding amounts of current to the motor. A torque from the motor is conveyed to the wheels as drive power by means of the car's transmission. A contact-type charging method is applied, using a cord running from the external charger to a plug in the engine compartment. The removal of conventional engine also eliminates the negative pressure used by the brake booster, and therefore a commercial vacuum pump designed for electric vehicles is mounted on the prototype vehicle. A DC-DC converter is installed to supply power to 12-V electrical equipment, and the power-hungry air conditioner has been removed, leaving the vehicle quite similar in function to a basic gasoline car. The weight of the prototype vehicle is about 1,200 kg.

Photo 2 shows the engine compartment with the superconducting motor, current controller, and batteries installed. The motor's compact design enables transverse installation and it thus leaves ample room in the engine compartment for the current controller, the DC-DC converter, the vacuum pump for brake assist, and two batteries.

The running evaluation results for the vehicle are shown in **Table 2**. As is characteristic of electric vehicles, the highest torque is obtained at low speeds; hence, smooth acceleration from a standstill is possible even when the vehicle is in third gear. The maximum verified speed was 70 km/hr, and it is suitable for use in normal driving.

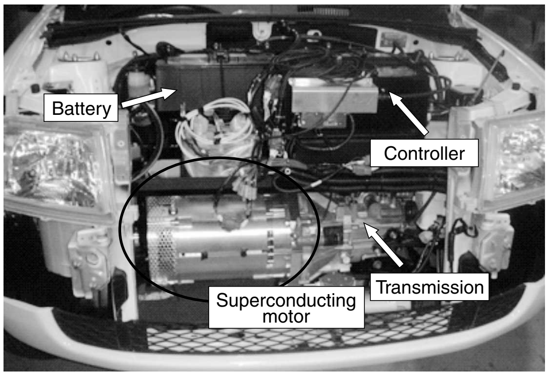

Photo 2. Superconducting motor fitted inside vehicle

Photo 3. Test drive

Table 2. Vehicle Performance

Items		Performance
Vehicle Performance	Maximum torque (1,000 rpm)	70Nm
	Maximum output (4,500 rpm)	18kW
	Maximum speed (3rd gear)	Above 70 km/hr
	Cruising distance (at 30 km/hr on test site)	36km

6. Conclusion

Hydrogen fuel is expected to become an environmentally-friendly energy source that provides one step toward realizing future low-carbon society. In the automotive field, progress has been made toward the development of fuel cell vehicles and hydrogen internal-combustion engine vehicles [9]. If liquid hydrogen is used as the fuel for such vehicles, the potential exists for making still greater use of the advantages of the superconducting motor. **Figure 7** is a conceptual diagram of a fuel-cell-powered superconducting motor vehicle drive system. It uses liquid hydrogen as the coolant for the superconducting motor. The boiling point of liquid hydrogen is about 20 K, which is below the critical temperature of high-temperature superconducting wire. Vaporized hydrogen is used as the fuel for the fuel cell. A characteristic of superconducting wire is that the lower the operating temperature, the stronger the electrical current in the superconducting state. Compared with the temperature of liquid nitrogen coolant (77 K), at the temperature of liquid hydrogen (20 K), current can be boosted several fold and thus a motor with higher torque should be possible. Therefore, the refrigerating unit for cooling the motor can be either eliminated or replaced by a low-capacity model. Thus the advantages of superconductivity could be optimally employed while keeping the cost of the system to a minimum.

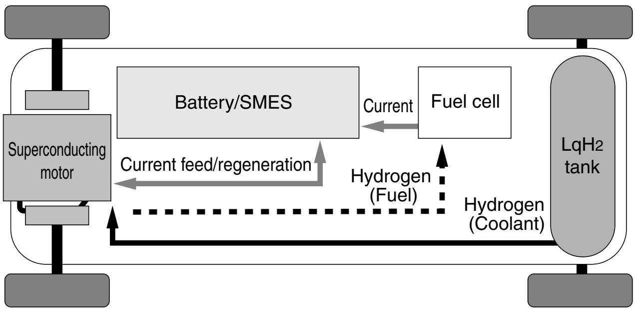

Fig. 7. Superconducting motor car (Fuel cell vehicle with liquid H_2 cooled motor)

The authors have developed a test prototype of an electric automobile powered by a motor using high-temperature superconducting wire and fitted with devices to supply power to the motor. In test driving over a six-month period up to April 2008, covering 200 km, the vehicle has operated smoothly without problems. The authors will continue compiling test-driving records to verify the reliability of the superconducting motor mounted on a vehicle and move forward with the research on more advanced superconducting motor systems with cooling devices that use the above-described liquid hydrogen cooling mechanism, with an aim of developing superconductor-applied products with excellent commercial viability.

References

(1) Toru Okazaki, Investigation of the Use of Superconductivity Drive to Make Moving Bodies Highly Efficient, SEI Technical Review, No. 168 (March 2006)

(2) Sugimoto et al., Trial Manufacture of High-Temperature Superconducting motor, Institute of Electrical Engineers of Japan National Convention (March 17, 2005), The University of Tokushima

(3) The World's First In-Grid Demonstration of Long-Length "3-in-One" HTS Cable (Albany Project), SEI Technical Review, No. 170 (January 2007)

(4) Climate Change 2007: The 4th Assessment Report of the Intergovernmental Panel on Climate Change http://www.env.go.jp/earth/ipcc/4th/interim-j.pdf

(5) Japan Ministry of Environment website http://www.env.go.jp/earth/cop6/3-2.html

(6) All about Hybrid and Electric Cars, 2007, Nikkei Business Publications, Inc.

(7) Potentials of Fuel Cell and Electric Vehicles, Grand Prix Shuppan

(8) Superconductivity Communications, Vol. 4, No. 1, Feb. 1996, Article E3.

(9) Omori et al., The Leading Edge of Hydrogen Energy, Kogyo Chosakai Publishing, Inc.

Contributors (The lead author is indicated by an asterisk (*)).

H. OYAMA*
• Manager, Electric Power and Energy Research Laboratories

T. SHINZATO
• Assistant Manager, Electric Power and Energy Research Laboratories

K. HAYASHI
• General Manager, Electric Power and Energy Research Laboratories

K. KITAJIMA
• Automotive Technology R&D Laboratories

T. ARIYOSHI
• Manager, Automotive Technology R&D Laboratories

T. SAWAI
• General Manager, Automotive Technology R&D Laboratories